

Reverse Noise Measurement and Use in Device Characterization^{*}

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Abstract — We review the concept of reverse noise measurements in the context of on-wafer transistor noise characterization. Several different applications of reverse noise measurements are suggested and demonstrated. Reverse measurements can be used to check measurement results, to significantly reduce the uncertainty in $|Γ_{opt}|$, to reduce the occurrence of nonphysical results, and possibly to directly measure or constrain parameters in models of transistors.

Index Terms — CMOS, noise, noise measurements, on-wafer measurements

I. INTRODUCTION

A two-port circuit component, be it active or passive, emits noise from both ports. Using direct measurement of the noise emerging from the input of an amplifier or a transistor was suggested some time ago [1,2] as a way to improve the determination of the noise parameters of the amplifier or transistor. The reverse noise from a low-noise device has been used to make synthetic cold noise sources [3–5], but with some exceptions [6,7] its use in noise-parameter measurements is not widespread. In this paper we present several ways of using reverse noise measurements to improve the noise characterization of transistors. We first briefly review the theoretical framework and describe the measurement method. We then demonstrate the use of reverse measurements as a method of checking on-wafer noise-parameter measurements. Reverse measurements can also be included in the fitting procedure for the noise parameters, and we show how this can reduce some uncertainties and also reduce the frequency of occurrence of nonphysical results. Finally, we suggest new applications for future work, based on direct extraction of model parameters.

II. THEORY AND MEASUREMENT METHOD

A. Theoretical Framework

Reverse noise measurements are most conveniently treated in terms of a wave representation of the noise

correlation matrix [2]. A linear two-port, such as that shown in Fig. 1, is described by $\mathbf{b} = \mathbf{S}\mathbf{a} + \mathbf{c}$, where \mathbf{a} , \mathbf{b} , and \mathbf{c} are two-dimensional column vectors, and \mathbf{S} is the 2×2 scattering matrix. The elements a_1 , b_1 and a_2 , b_2 are the wave amplitudes of the incident (\mathbf{a}) and emergent (\mathbf{b}) waves at planes 1 and 2 (the input and output planes of the device), and c_1 , c_2 are the wave amplitudes due to the intrinsic noise of the device. The wave amplitudes are normalized such that $|a_i|^2$ is a spectral power density. The intrinsic noise correlation matrix is defined as $N_{ij} \equiv \langle c_i c_j^* \rangle$, where the brackets denote a time or ensemble average (assumed to be equal). For notational convenience, we define $X_1 \equiv N_{11}$, $X_2 \equiv N_{22}/|S_{21}|^2$, $X_{12} \equiv N_{12}/S_{21}^*$, and use the X 's as our set of noise parameters [8]. Since the familiar IEEE noise parameters can be written in terms of the elements of the noise correlation matrix [2], they can also be expressed in terms of the X parameters. (The S-parameters also enter into the transformations.) The inverse transformations also exist. In the interests of space, we do not reproduce the transformations here, but if one knows one set of noise parameters and the S-parameters, then the other set can be computed.

In terms of the X 's, the noise temperature T_1 at plane 1, looking into the input of the device, is given by [8]

$$T_1 = \frac{1}{(1-|\Gamma_1|^2)} \left\{ \frac{|S_{12}|^2(1-|\Gamma_G|^2)}{|1-\Gamma_G S_{22}|^2} T_G + \left| \frac{\Gamma_G}{1-\Gamma_G S_{11}} \right|^2 \times \right. \\ \left. X_2 + X_1 + 2 \operatorname{Re} \left[\frac{S_{12} S_{21} \Gamma_G X_{12}^*}{1-\Gamma_G S_{22}} \right] \right\}, \quad (1)$$

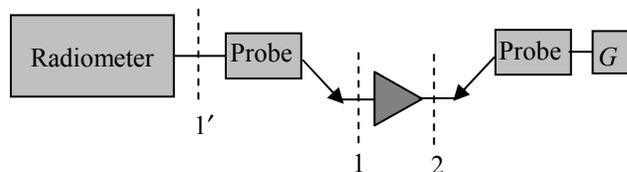


Fig. 1 Measurement configuration for T_1 .

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where Γ_G and T_G are the reflection coefficient and noise temperature of the termination G at plane 2, and Γ_1 is the reflection coefficient looking into the input of the device at plane 1. (Note: (6) of [8] incorrectly has X_{12} rather than X_{12}^* .)

B. Measurement Method

The configuration for reverse noise measurement on a wafer is indicated in Fig. 1. An on-wafer calibration is required in order to determine the S-parameters of the probe (between plane 1 and plane 1'), the S-parameters of the DUT between 1 and 2, Γ_G (at plane 2), and Γ_1 . The noise temperature $T_{1'}$ at plane 1' can be measured with a normal coaxial noise-temperature measurement. To determine the noise temperature at plane 1, the probe from 1 to 1' can then be treated as an adapter, and its available power ratio $\alpha_{1'1}$ can be calculated from its S-parameters and Γ_1 . The noise temperature at plane 1 is then given by

$$T_1 = \frac{T_{1'} - (1 - \alpha_{1'1})T_a}{\alpha_{1'1}}, \quad (2)$$

where T_a is the (ambient) temperature of the probe.

All measurement results in this paper were obtained on the same device, designed by RF Micro Devices (RFMD) and fabricated by IBM for this work as part of the Kelvin Project. It is a $128 \times 3 \times 0.12$ NMOS device in which there are 128 fingers of polysilicon over a $3 \mu\text{m}$ wide active channel, with a transistor drawn gate length of $0.12 \mu\text{m}$ processed in $0.13 \mu\text{m}$ CMOS process technology. It was biased with a drain voltage $V_{ds} = 1.2 \text{ V}$ and a drain current density $J_{ds} = 25 \mu\text{A}/\mu\text{m}$. The saturated drain current density for this process is approximately $600 \mu\text{A}/\mu\text{m}$, so this bias represents a weak inversion operating condition, potentially useful for low-noise-amplifier design [9]. This transistor with this set of bias conditions is referred to as R2 in the figures. Each of the three laboratories (IBM, NIST, RFMD) had its own die with a copy of this transistor, so that measurements at different laboratories were not performed on the same actual physical device.

III. APPLICATIONS

A. T_1 as a Check of Measured Noise Parameters

The simplest use of a measurement of T_1 is as a check of noise-parameter results obtained from a series of forward measurements. For this purpose, the output termination is usually chosen to approximate a matched (i.e., reflectionless) load, so that $\Gamma_G \approx 0$ in (1). One then performs a direct measurement of T_1 and compares the result to the prediction obtained from the measured noise

parameters. This check method has been suggested and used in noise-parameter measurements of amplifiers [7], and we have now used it for on-wafer noise-parameter measurements of transistors as well. Fig. 2 shows results of direct measurements of T_1 compared to predictions based on measured noise parameters for the transistor R2 described in Section II.B. The noise parameters were measured with a popular commercial system, employing forward noise measurements with a series of ambient-temperature terminations with differing reflection coefficients and one hot termination [10,11]. The commercial system yields measured values of the S-parameters and the IEEE noise parameters F_{min} , R_n , $|\Gamma_{opt}|$, and ϕ_{opt} . These were converted to X's, and the predicted T_1 was computed from (1), without using approximations based on small $|\Gamma_G|$, or small $|S_{12}|$, etc. The value for Γ_G in (1) was measured in the T_1 measurement. At most of the higher frequencies, the direct-measurement results agree quite well with the values predicted on the basis of the measured noise parameters; but below about 4 GHz, there is a clear discrepancy between the two, suggesting a problem with the noise-parameter measurements at the lower frequencies in this case (or, in principle, with the direct measurement of T_1).

The fact that T_1 is considerably below ambient temperature may seem peculiar at first. It does not violate any fundamental thermodynamic principles because the transistor is not an isolated system; power is being supplied to it from outside. In this sense, one can consider the transistor to be a small electronic refrigerator, which uses externally supplied power to produce a region colder than ambient (the input) by pumping noise to a region hotter than ambient (the output). Skeptics may be reassured by the fact that we have reproduced such qualitative behavior with simulations based on circuit models of transistors.

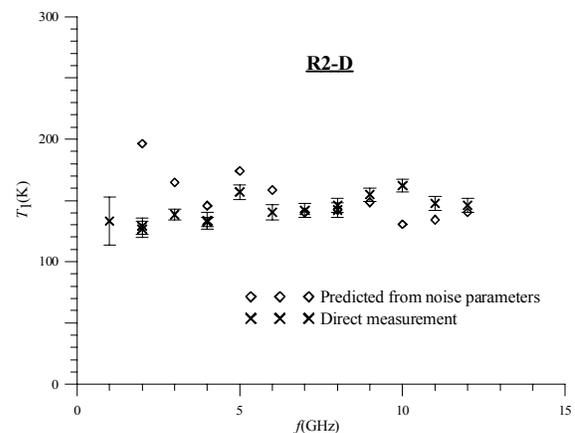


Fig. 2 Comparison of direct measurements of T_1 with predictions based on measured noise parameters.

B. Use of Reverse Measurements to Reduce Noise-Parameter Uncertainties

The result of a reverse measurement can also be included in the fitting procedure, as has been done for amplifier noise parameters [6–8]. (In fact, a recent paper [12] reports measurements of a transistor’s noise parameters using *only* reverse measurements.) For the amplifier case, it was found that including a reverse measurement in the fit did not usually reduce the uncertainties in the IEEE noise parameters. For a transistor with large $|F_{opt}|$, $|S_{11}|$, and $|S_{22}|$, however, there can be some benefit. The benefit can come in two forms: reduction of uncertainties and reduction of the rate of occurrence of nonphysical results.

The effect of a reverse measurement on the uncertainties in IEEE noise parameters was investigated with an extended version of the Monte Carlo program of [8]. The original amplifier applications were restricted to relatively small values of $|F_{opt}|$ (less than about 0.4), so the program was modified and extended to allow its application to values of $|F_{opt}|$ up to one. The uncertainties depend on a large number of factors, including the actual values of the noise parameters and S-parameters, which noise parameter is being considered, the number of input terminations, the distribution of the reflection coefficients of those terminations, the values chosen for the underlying uncertainties, etc. A more complete study will be published elsewhere; here we present only some representative results.

The effect of including a reverse noise measurement is most dramatic in the uncertainty in $|F_{opt}|$. An example is shown in Fig. 3, which plots the estimated uncertainty in $|F_{opt}|$ for a set of forward measurements (eight different ambient-temperature input terminations plus one hot termination) and for the same set of forward measurements plus one reverse measurement. The noise parameters used in the evaluation were results of actual measurements on the transistor R2 [13]. It is clear from Fig. 3 that including a reverse measurement significantly reduces the uncertainty in $|F_{opt}|$, often by a factor of two or more. The effect on the uncertainties in other IEEE noise parameters is small, and occasionally in the wrong direction. A note of caution is that these results were obtained with non-optimized sets of input terminations. Results with better sets of input reflection coefficients could be less dramatic.

An improvement in the knowledge of $|F_{opt}|$ can be an important factor in designing circuits with low noise figures, since the minimum value is achieved for an input reflection coefficient equal to F_{opt} . This is particularly true for FETs, which have a relatively high value of R_n (compared for example to HBTs), and whose noise figures

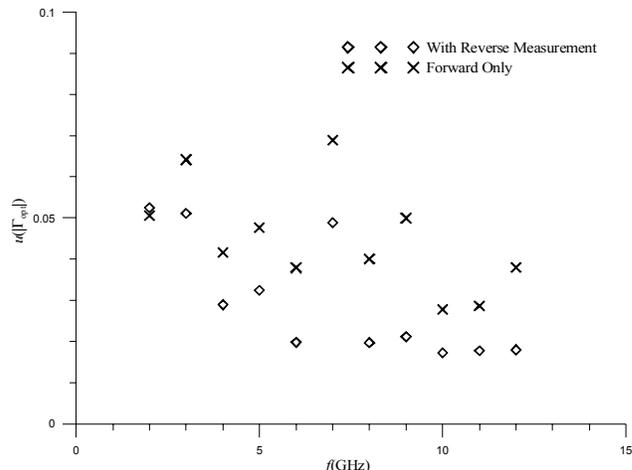


Fig. 3 Comparison of standard uncertainty in $|F_{opt}|$, with and without inclusion of a measurement of T_1 .

are therefore more sensitive to the match achieved at the transistor input.

The other benefit of including reverse measurements in the noise-parameter analysis is that it can reduce the occurrence of nonphysical results. There are a number of physical constraints on the noise parameters of a linear two-port. Some constraints, such as $F_{min} > 0$, are obvious. Some constraints are only obvious if expressed in terms of a propitious parameter set; e.g., in terms of the X parameters, it is obvious that X_1 must be greater than zero, but when expressed in terms of the IEEE parameters it is far from obvious. Other constraints [14] are not immediately obvious in any parameter set. Due to the errors that enter any actual measurements, it is possible to obtain noise-parameter results that violate one or more of these physical constraints (unless the fitting routine is constrained to return only “physical” results). This is particularly true when one is dealing with a device whose noise parameters are close to physical boundaries, such as very small F_{min} or $|F_{opt}|$ or $|S_{11}|$ very near 1. In such cases, inclusion of a reverse measurement in the analysis can reduce the likelihood of obtaining results that violate a physical bound. We have performed Monte Carlo simulations of the effect and find that although the improvement is usually too small to be significant, there are exceptional cases where the probability of a nonphysical result can be reduced from about 15 % to below 5 %.

To use T_1 to improve the determination of the noise parameters, it is necessary not only to measure T_1 , but also to include it in the fitting program, performing a simultaneous fit to both forward and reverse measurements [6] – [8]. For most present systems, this would require a new (reverse) measurement configuration

and a modification of software, but the potential benefits could make such modifications worthwhile.

C. Direct Comparison to Model Results or Parameters

Possibly the most interesting application of reverse noise measurements is to use such measurements directly to constrain or determine parameters in a model of the transistor, without any recourse to a noise-parameter measurement. This application is still in development, but an example of the sort of measurement results that can be obtained, and that must be explained by any complete model, is shown in Fig. 4, which plots the measured reverse noise temperature T_1 (for a nearly reflectionless termination at plane 2) as a function of the drain voltage V_{ds} . Any successful model will have to reproduce not just the correct magnitude, but also the clear linear dependence on V_{ds} . It is hoped that such measurements will open a new window on the underlying physics of the devices being measured.

IV. CONCLUSIONS

We have outlined several applications of reverse noise measurements in the determination of transistor noise characteristics. Measurement of the reverse noise temperature can be used as a check of noise-parameter results obtained from conventional forward measurements, or it can be used to augment the forward measurements, by including it in the measurement results to be fitted. In the latter case, it can improve the uncertainties, particularly of $|F_{opt}|$, and it typically reduces the likelihood of obtaining results that violate physical bounds. Finally we raised the possibility that reverse noise measurements will offer a direct insight into facets of device models that are not easily accessible by other means.

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REFERENCES

- [1] D. Wait and G. Engen, "Application of radiometry to the accurate measurement of amplifier noise," *IEEE Trans. Instrum. and Meas.*, vol. 40, no. 2, pp. 433-437, April 1991; correction: *ibid*, vol. 42, no. 1, p. 78, Feb. 1993.
- [2] S. Wedge and D. Rutledge, "Wave techniques for noise modeling and measurement," *IEEE Trans. Microwave Theory & Tech.*, vol. 40, no. 11, pp. 2004-2012, Nov. 1992.
- [3] R. Frater and D. Williams, "An active 'cold' noise source," *IEEE Trans. Microwave Theory & Tech.*, vol. MTT-29, no. 4, pp. 344-347, April 1981.

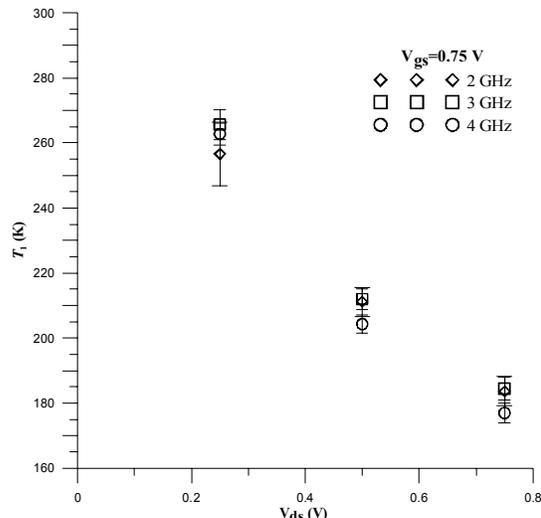


Fig. 4 Dependence of T_1 on V_{ds} .

- [4] L. Dunleavy, M. Smith, S. Lardizabal, A. Fejzuli, and R. Roeder, "Design and characterization of FET based cold/hot noise sources," *IEEE MTT-S Digest*, pp. 1293-1296, May 1997.
- [5] P. Buhles and S. Lardizabal, "Design and characterization of MMIC active cold loads," *IEEE MTT-S Digest*, pp. 29-32, June 2000.
- [6] D. Wait and J. Randa, "Amplifier noise measurements at NIST," *IEEE Trans. Instrum. and Meas.*, vol. 46, no. 2, pp. 482-485, April 1997.
- [7] J. Randa and D. Walker, "Amplifier noise-parameter measurement checks and verification," *63rd ARFTG Conference Digest*, pp. 41-45, June 2004.
- [8] J. Randa, "Noise-parameter uncertainties: a Monte Carlo simulation," *J. Res. NIST*, vol. 107, pp. 431-444, Sept. 2002.
- [9] D. Shaeffer and T. Lee, "A 1.5-V 1.5 GHz CMOS low noise amplifier," *IEEE J. Solid-State Circuits*, vol. 32, pp. 745-759, March 1997.
- [10] V. Adamian and A. Uhlir, "Simplified noise evaluation of microwave receivers," *IEEE Trans. Instrum. and Meas.*, vol. IM-33, no. 2, pp. 136-140, June 1984.
- [11] V. Adamian, "2 - 26.5 GHz on-wafer noise and S-parameter measurements using a solid state tuner," *34th ARFTG Conference Digest*, pp. 33-40, Nov. 1989.
- [12] M. Weatherspoon and L. Dunleavy, "Experimental validation of generalized equations for FET cold noise source design," *IEEE Trans. Microwave Theory & Tech.*, vol. 54, no. 2, pp. 608 - 614, Feb. 2006.
- [13] J. Randa *et al.*, "Interlaboratory comparison of noise-parameter measurements on CMOS devices with 0.12 μm gate length," *66th ARFTG Conference Digest*, pp. 77-81, Dec. 2005.
- [14] M. Pospieszalski and W. Wiatr, "Comments on 'Design of microwave GaAs MESFETs for broad-band, low-noise amplifier'," *IEEE Trans. Microwave Theory & Tech.*, vol. MTT-34, no. 1, p. 194, Jan. 1986.

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